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L. D. SMULLIN
J. E. BAGNALL

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ABSTRACT

The electronic tuning and loading of a cutoff QK-61 magnetron are measured as functions of anode voltage, magnetic field, r-f signal level and heater voltage. The regions corresponding to d-c cutoff and to resonance of the space charge are identified. The results are compared with the theoretical predictions of Lamb and Phillips.

SOME MEASUREMENTS OF THE CHARACTERISTICS OF A CUTOFF MAGNETRON

Introduction

In the course of our studies of techniques for modulating microwave signals, a brief investigation of the characteristics of a cutoff magnetron was made. The object of the experiment was to determine whether it would be suitable for use as a reactance tube. The idea of using a magnetron as a reactance tube has been considered by a number of workers (1)(2)(3)(4)(5)(6). None of the reports of experimental work, however, give any detailed picture of the nature of the impedance variation to be obtained from such a tube; in particular, no mention is made of the magnitude of the real component of the impedance. Obviously, the performance of a reactance tube will be strongly dependent upon the ratio R/X which can be obtained.

In the experiments to be described, the resonance frequency and loaded Q of a Raytheon QK-61 (c-w) magnetron were measured as functions of d-c anode voltage, magnetic field, cathode temperature, and r-f signal level. The results are compared with the small-signal theory of Lamb and Phillips(4).

Experimental Results

The QK-61 magnetron is a 16-vane, tunable, c-w magnetron, designed to operate at anode voltages from 500 to 1200 volts and to generate up to about 100 watts of power. The cathode diameter is $2r_c = 0.136$ inches, the anode diameter is $2r_a = 0.226$ inches, giving a ratio $\sigma = r_c/r_a = 0.6$. The loaded and unloaded Q 's of the tube described here were $Q_{L1} = 198$, $Q_0 = 1140$, giving an apparent input conductance $g_0/y_0 = 0.21$.

Some uncertainty exists as to the exact value of the magnetic fields used in these tests. This arises from the fact that the magnetron has built-in iron pole pieces so that the actual field in the air gap could never be measured except by calibrating the magnet with what was presumed to be an identical set of dummy pole-pieces. The maximum value of this uncertainty is estimated to be about 5 per cent.

The measurements were made in the following way. The mechanical tuning control of the magnetron under test was calibrated, and was found to be accurately resettable. The magnetron was connected to one arm of a coaxial hybrid junction, with a short circuit on the opposite arm adjusted to give minimum transmission with the magnetron detuned. Thus, the transmission characteristics of the junction were those of a simple resonant circuit with the same tuning and loaded Q of the magnetron. During a given measurement, the

frequency of the test signal was kept constant, and the tuning control was adjusted to tune the magnetron to the test signal. This constituted a substitution measurement in which the electronic susceptance was compensated by the mechanical tuning. The loaded Q was measured in terms of the mechanical tuning necessary to reduce by one-half the power transmitted past the magnetron.

Tuning vs. Anode Voltage and Magnetic Field

Figure 1 presents the variation of resonant wavelength and electronic loading ($1/Q_e$) of the cutoff magnetron as a function of anode voltage, with magnetic field as a parameter. It is apparent that regions of most rapid change of tuning correspond to rapid changes in, and large values of, electronic loading. Figure 2 shows tuning and $1/Q_e$ as functions of magnetic field with anode voltage as a parameter. The data for these two sets of curves were taken with an incident r-f power of 14 mw.

Although any practical modulation scheme would depend on voltage control, it is perhaps more instructive to examine the effect of magnetic field as indicated in Figure 2. Two prominent sets of minima appear in the tuning curves of Figure 2 (the corresponding $1/Q_e$ curves exhibit maxima); they are identified as A and B. The minima in group A occur at magnetic fields corresponding to the cutoff for the particular anode voltage. This correspondence is demonstrated in Table I, where the calculated cutoff fields for various anode voltages are compared with the magnetic field at the minimum of each of the corresponding voltage curves in Figure 2(a).

Table I					
Anode Voltage	75	100	125	150	175
B _{cutoff} (calculated) (gauss)	312	361	404	412	478
B (experimental) (gauss)	330	380	420	470	520

The other group of minima (B) are not so easily identifiable. They apparently correspond to the cyclotron type of resonance described by Lamb and Philips(4), although the agreement with the formulae presented in that paper is very poor. The theory assumes a very small electron-cloud radius, no initial electron velocities, and ignores loss of r-f energy to the electrons. It states that the r-f impedance of the electron cloud becomes infinite at a frequency $\omega_c = eB/m$. For finite, but still small, electron-cloud thickness, the resonance frequency is modified as follows(4):

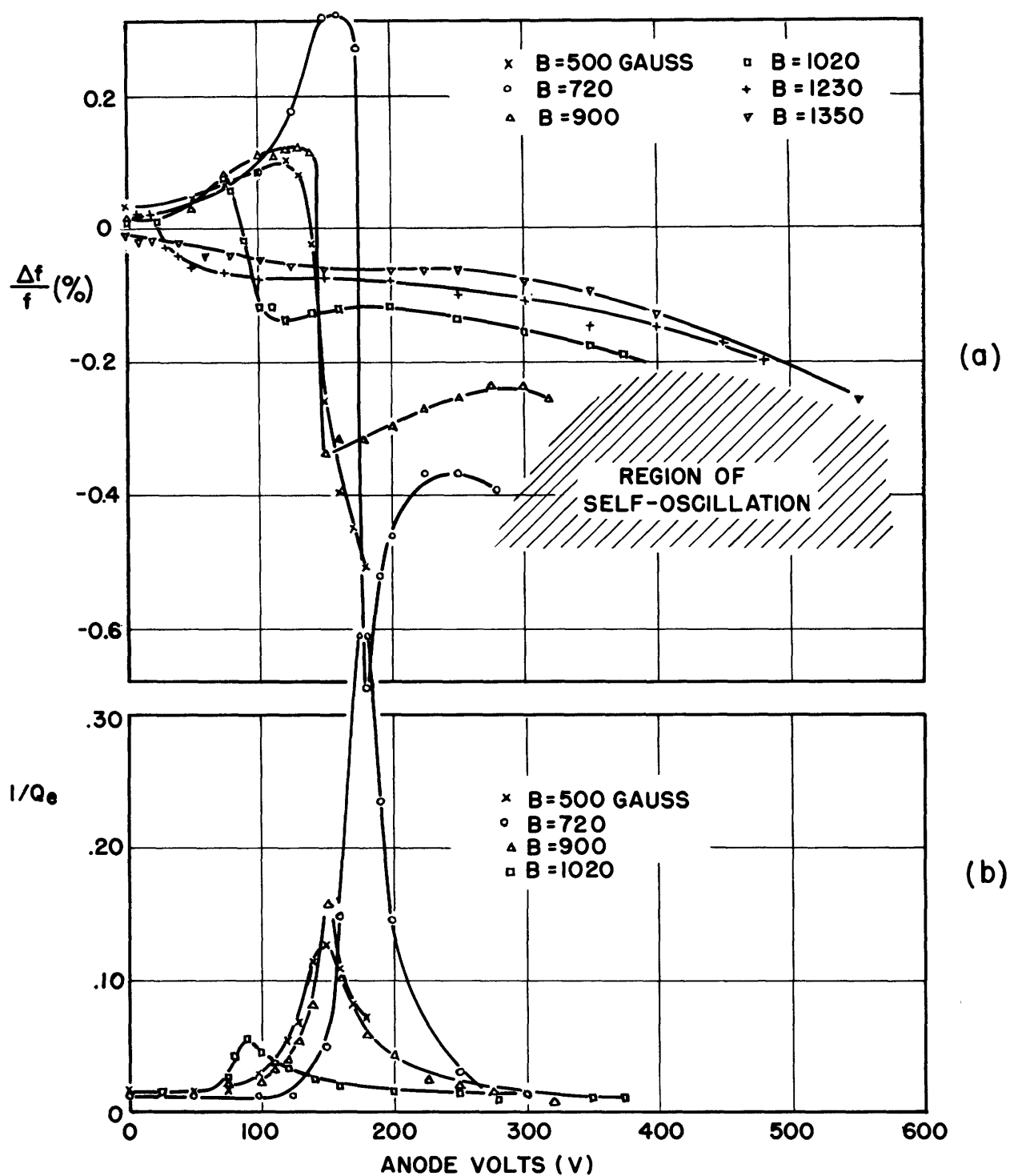


Fig.1 QK-61 magnetron: electronic tuning as a function of anode voltage; incident r-f power = 14 mw; heater voltage = 6.3 volts.

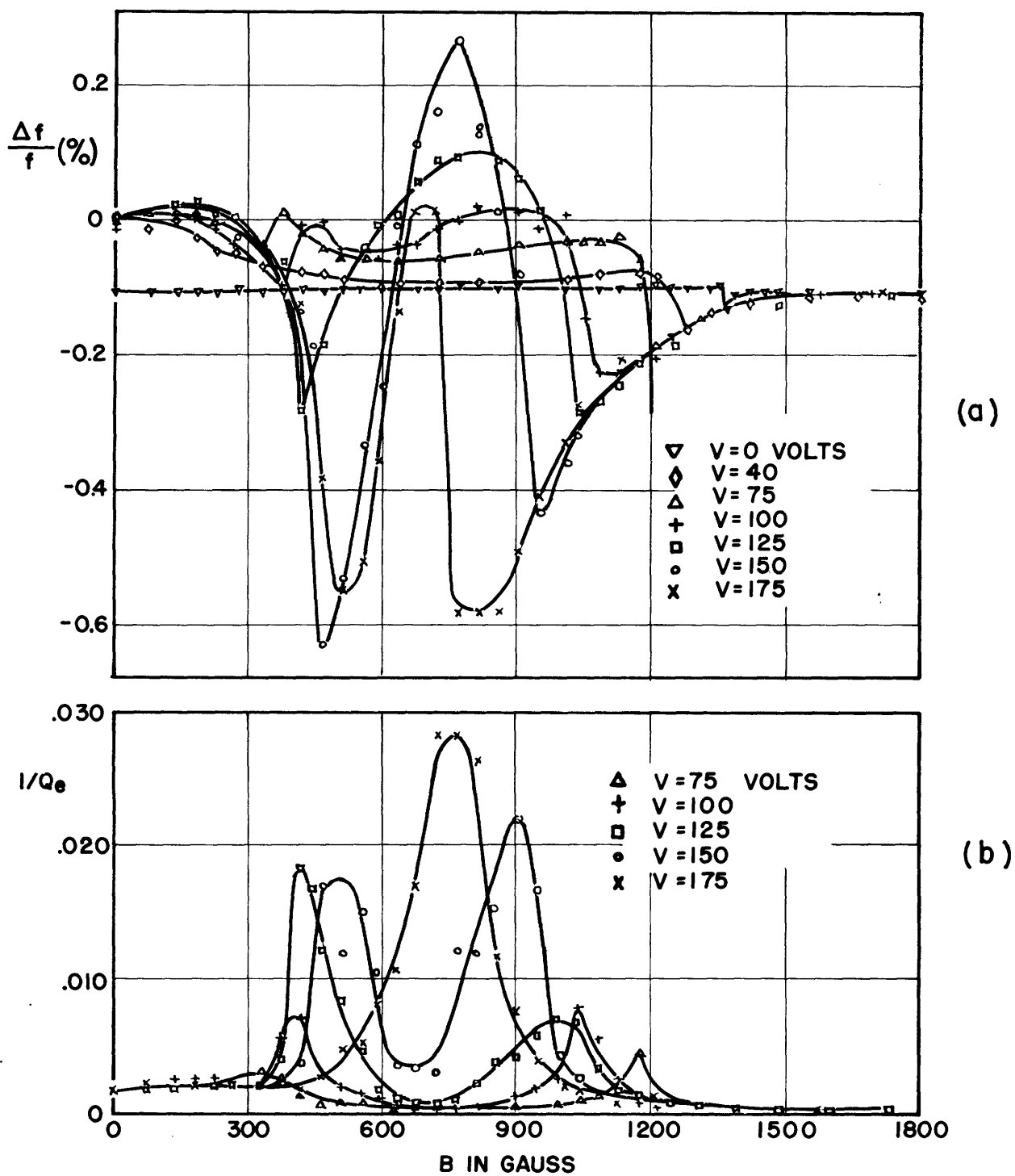


Fig.2 QK-61 magnetron: electronic tuning as a function of magnetic field; incident r-f power = 14 mw; heater voltage = 6.3 volts.

$$\omega_c' = \omega_c \left(1 + \frac{3}{2} \frac{ny}{r_c}\right) , \quad (1)$$

where y = thickness of electron cloud = $r_e - r_c$, and n = number of resonators. The cloud radius may be computed from the implicit relation

$$V = \left(\frac{m}{e}\right) \left(\frac{\omega_c}{8}\right)^2 r_e^2 \left[\left(1 - \frac{r_c^2}{r_e^2}\right)^2 + 2 \left(1 - \frac{r_c^4}{r_e^4}\right) \ln \frac{r_a}{r_e} \right] . \quad (2)$$

Figure 3 is a plot of this equation for $r_c/r_a = 0.6$. Table II gives ω_c' as computed from the observed values of voltage and field at the "B" minima.

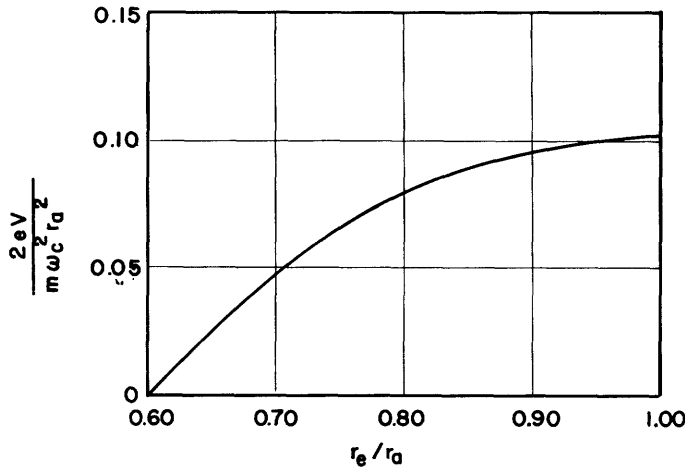


Fig.3 Electron-cloud radius for $r_c/r_a = 0.6$, plotted from Eq.(2).

Table II							
Anode Voltage	0	40	75	100	125	150	175
B_c (gauss)	1360	1250	1180	1030	1000	1000	730
$1 + 3ny/2r_c$	1.00	1.20	1.28	1.43	1.69	2.02	2.80
ω_c' ($\times 10^{-10}$)	2.40	2.64	2.69	2.60	2.96	3.20	3.72
$\omega_0 = 2\pi f_0 = 1.96 \times 10^{10}$ = test frequency							

The agreement at zero voltage can be made much better if we use Slater's formula for the critical field in a cylindrical magnetron(7). This substitution results in

$$\omega_c'' = \omega_c \left(\frac{1}{1 + \frac{1}{3/n}}\right) = \frac{eB}{m} \left(\frac{1}{1 + \frac{1}{3/n}}\right) . \quad (3)$$

Using $B_c = 1360$ gauss, $n = 16$, we find $\omega_c'' = 2.01 \times 10^{10}$ for zero anode voltage, as compared with the actual angular frequency of 1.96×10^{10} .

If a further empirical correction is made, namely changing Eq.(1) to read

$$\omega_c''' = \omega_c'' \left(1 + \frac{3}{4} \frac{ny}{r_c} \right) \quad (4)$$

where ω_c'' is given by Eq.(3), the agreement with experiment becomes much better, as shown in Table III.

Table III							
Anode Voltage	0	40	75	100	125	150	175
ω_c' ($\times 10^{-10}$)	2.40	2.64	2.69	2.60	2.96	3.20	3.72
ω_c''' ($\times 10^{-10}$)	2.01	2.03	2.00	1.94	1.99	2.00	2.11
ω_o ($\times 10^{-10}$)	1.96	1.96	1.96	1.96	1.96	1.96	1.96

Leakage Current

In making the measurements described above, it was observed that although the magnetron was nominally "cutoff", a small current did flow to the anode. This current was of the order of a few microamperes. When the magnetron was operated at a critical point in either region A or region B, it was noted that the anode current was a function of the setting of the mechanical tuner of the magnetron. With the magnetron cavity detuned relative to the signal frequency, the current was a maximum; it fell to a minimum when the magnetron was tuned to the signal frequency. This phenomenon seems to indicate an actual space current as opposed to "end leakage". The decrease of current at resonance is probably due to absorption of energy by the electrons, which results in their being driven back to the cathode where the energy is dissipated as heat.

Cathode Temperature

Figure 4 is a plot of tuning against magnetic field for several different values of heater voltage, with the anode voltage fixed at 100 volts and 14 mw of incident power. Although the cathode is designed to deliver more than 150 ma with a heater voltage of 6.3 volts, there is a marked dependence of electronic tuning upon heater voltage, even though the current flowing to the anode is only 10 to 20 microamperes. This behaviour seems to check

some predictions made by R. Q. Twiss of this Laboratory. In an as-yet-unpublished work, he has shown that the current leaving the cathode in a cutoff magnetron may be temperature-limited under certain conditions. Thus, even though the net cathode current is small, the circulating space-charge density may be very sensitive to the cathode emissivity, or temperature.

Incident Power Level

The effect of incident power upon electronic tuning and loading is illustrated in Figures 5 and 6. A rather unexpected result is that not only the maximum frequency excursion falls off markedly with increasing power, but the electronic loading also falls off rapidly. Although no large-signal theory of a cutoff magnetron has been developed, the reduced electronic loading at higher power levels is contrary to what had been expected(8).

Input Impedance

This series of measurements was made to study the magnetron as a reactance tube; i.e., as a circuit element. Therefore, it is perhaps more instructive to examine the input admittance as a function of V and B, instead of the curves of tuning and Q. Figure 7 has been plotted from the data in Figure 1. The electronic conductance is given by

$$g_e = g_o \frac{Q_o}{Q_e} = \frac{240}{Q_e} , \quad (5)$$

and the electronic susceptance is

$$b_e = 2(1 + g_o) Q_{L1} \frac{\Delta f}{f} = 478 \frac{\Delta f}{f} , \quad (6)$$

where $g_o = 0.21$, $Q_{L1} = 198$, $Q_o = 1140$.

The ratio b_e/g_e is plotted in Figure 8, for the same conditions as in Figure 7. This shows clearly that, in the region of maximum tuning rate, the figure of merit b_e/g_e is the lowest.

Figure 9 is a plot of the magnetron admittance as a function of magnetic field, for a fixed anode voltage. The points were computed from the curves of Figure 2.

Examination of Figure 7 indicates that there are regions where one can get an essentially constant conductance and a varying susceptance by using an appropriate length of line between the magnetron and the measuring terminals. The tuning range which one can get is small, however, and does not exceed a few megacycles per second, if a reasonably constant value of conductance is required.

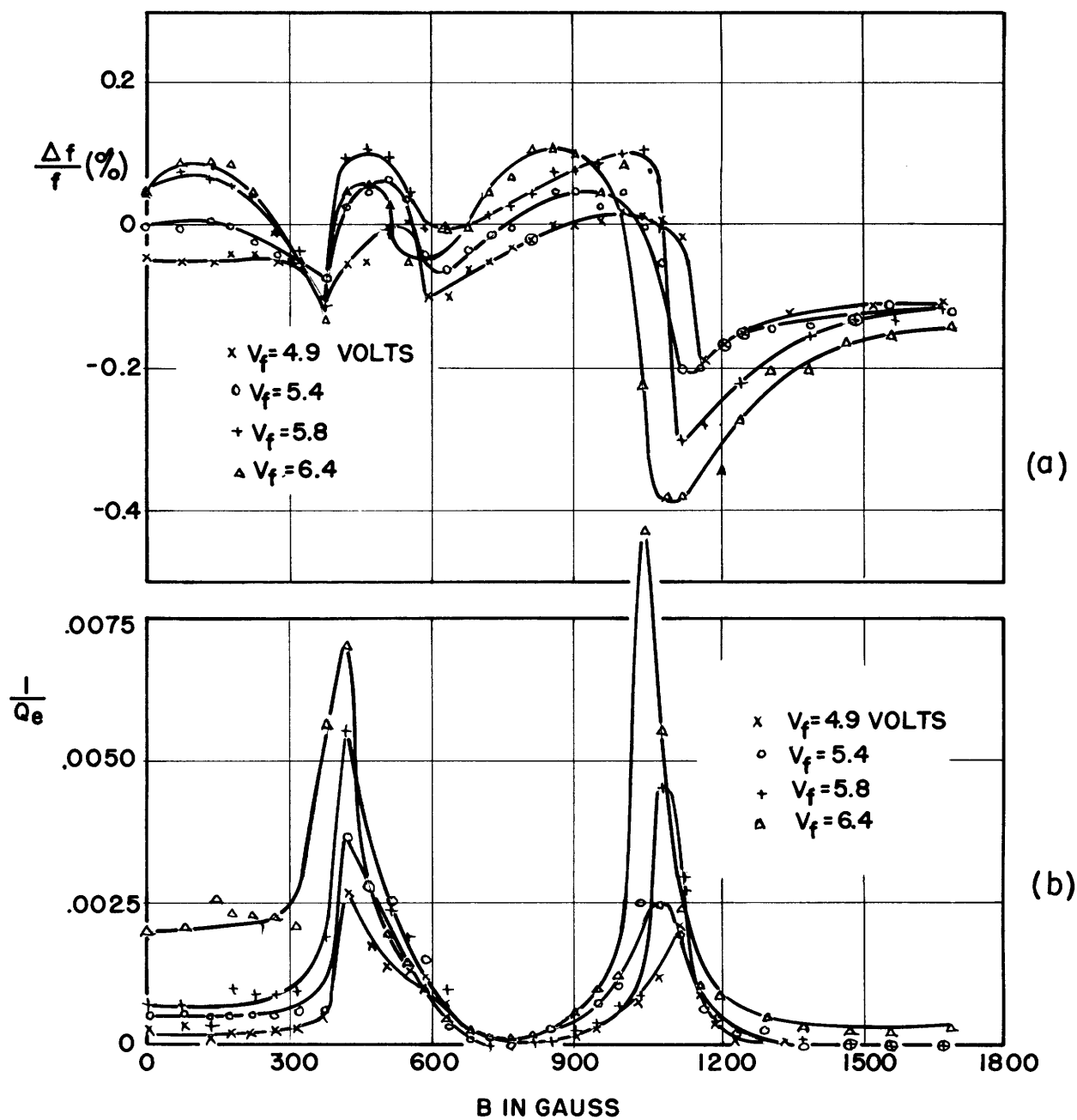


Fig.4 QK-61 magnetron: electronic tuning as a function of magnetic field for various heater voltages (V_f); incident r-f power = 14 mw.

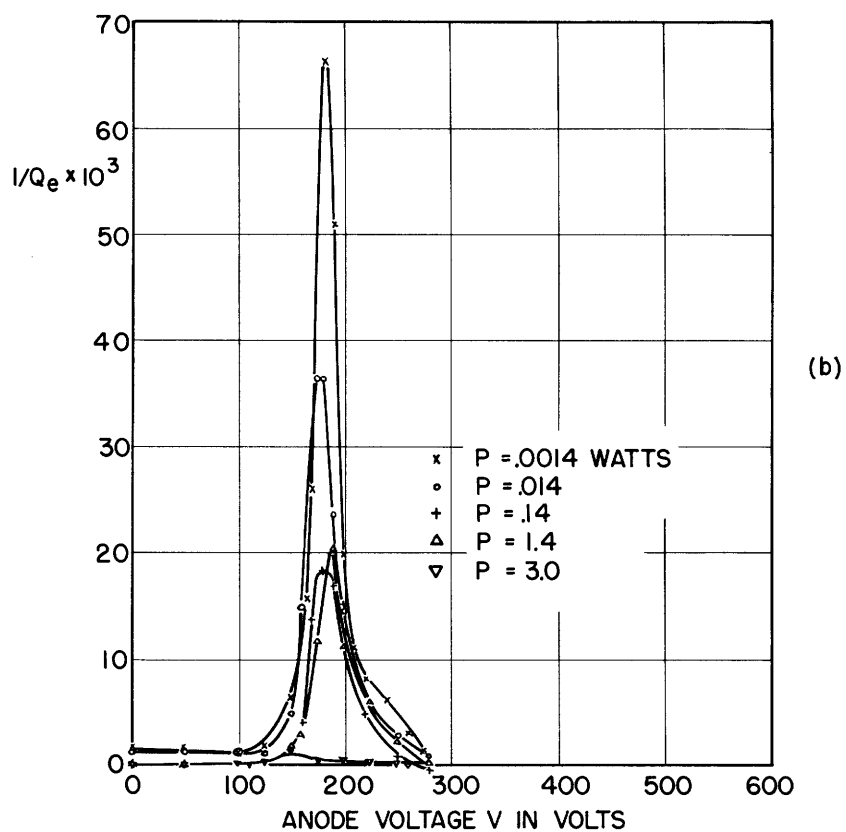
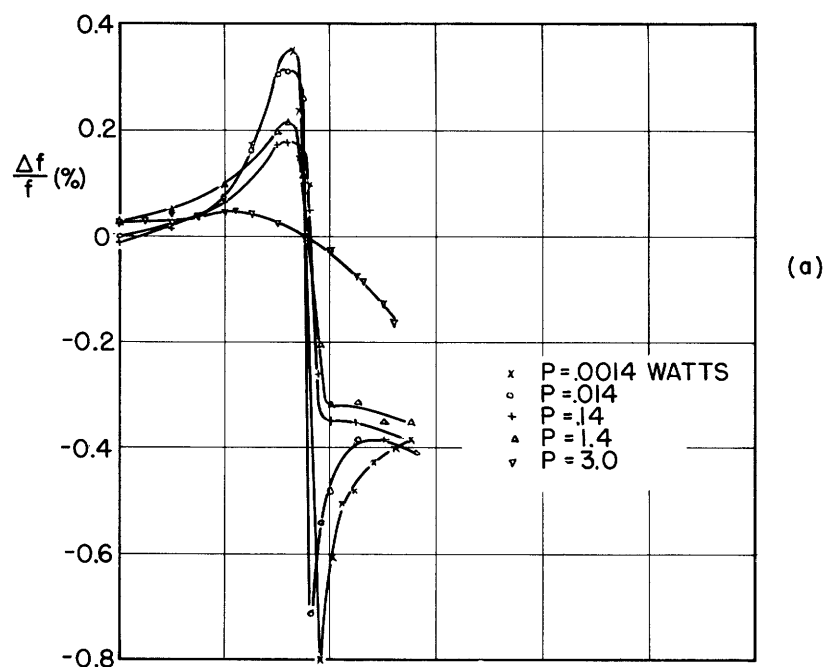


Fig.5 QK-61 magnetron: electronic tuning as a function of anode voltage for various levels of incident r-f power; heater voltage = 6.3 volts; magnetic field = 700 gauss.

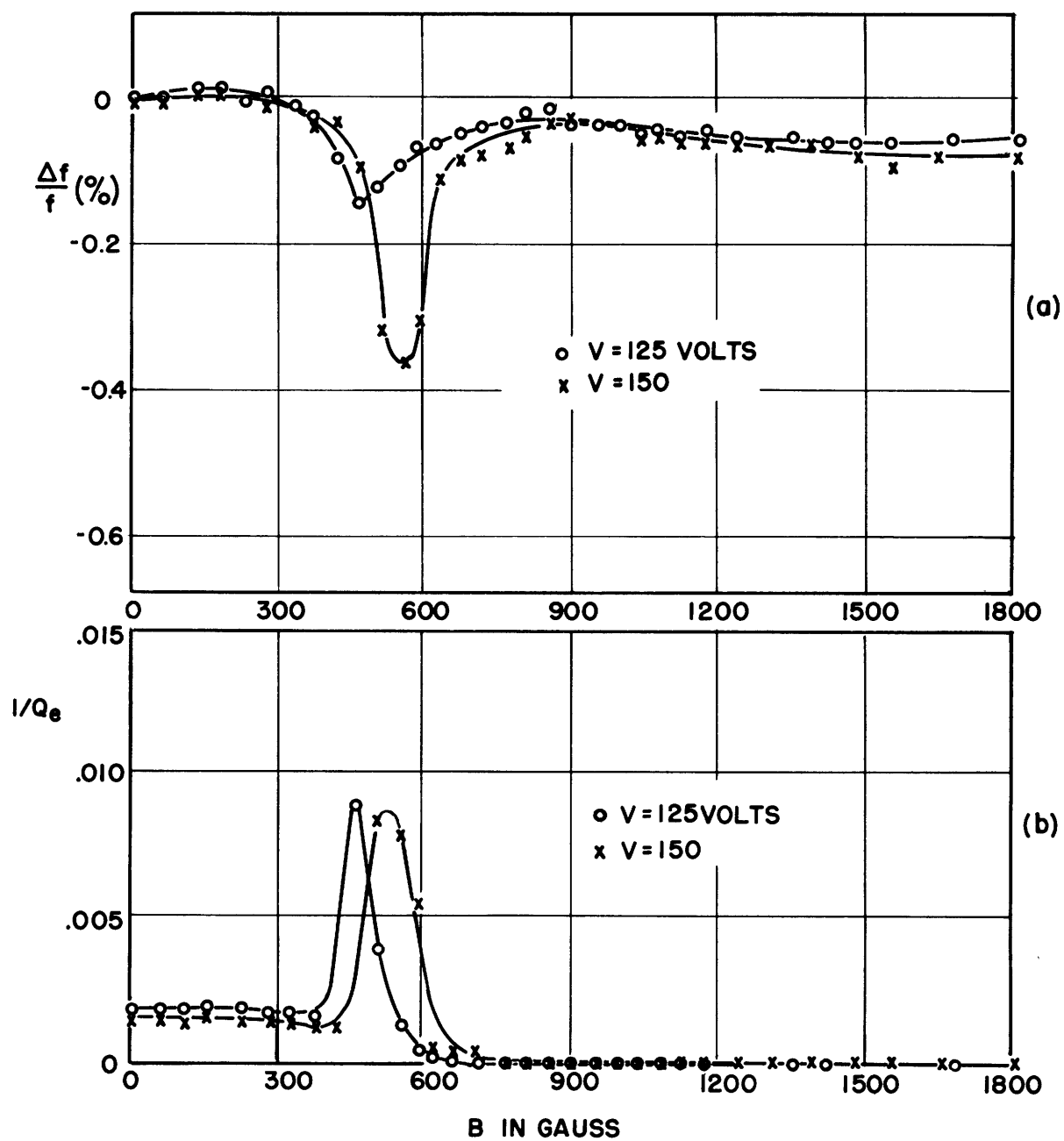
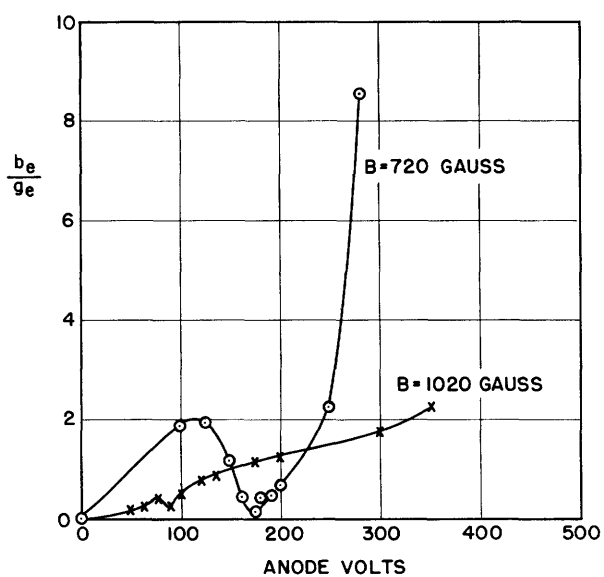
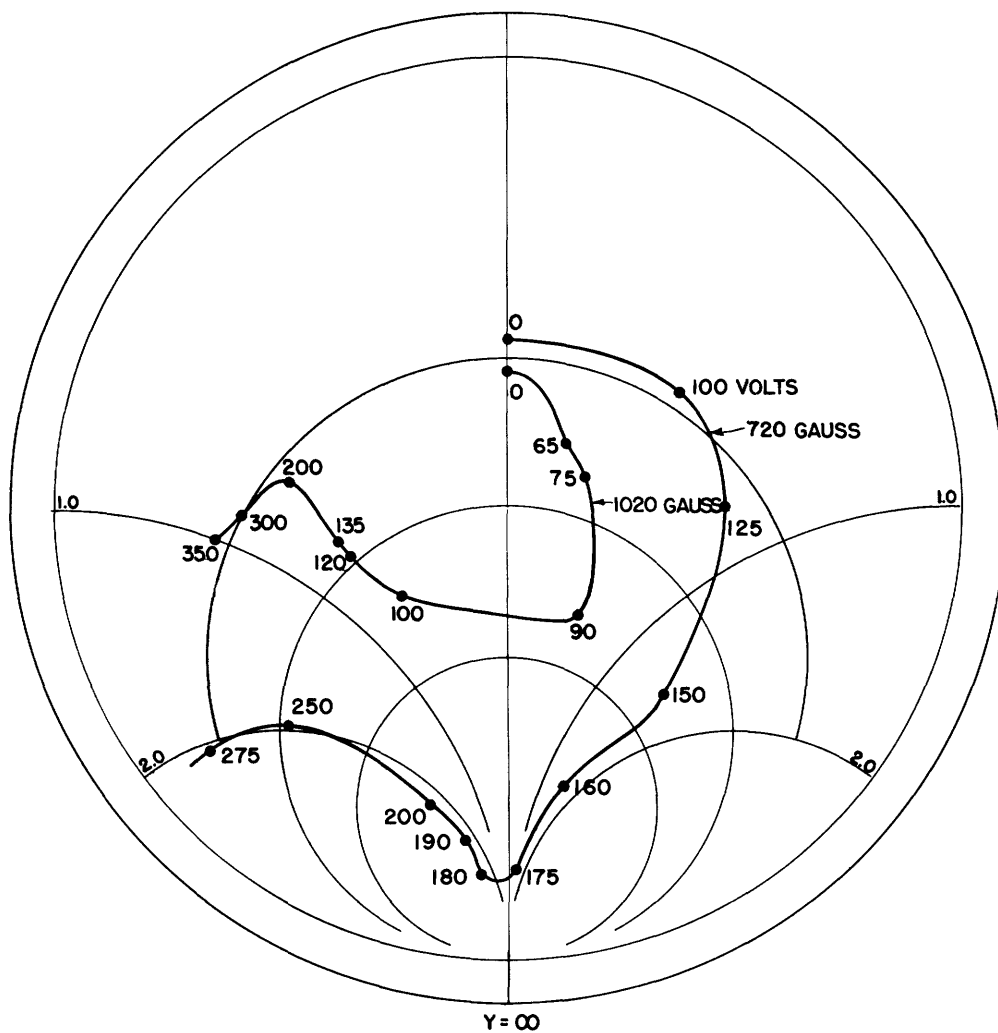


Fig.6 QK-61 magnetron: electronic tuning as a function of magnetic field; incident r-f power = 3.0 watts.



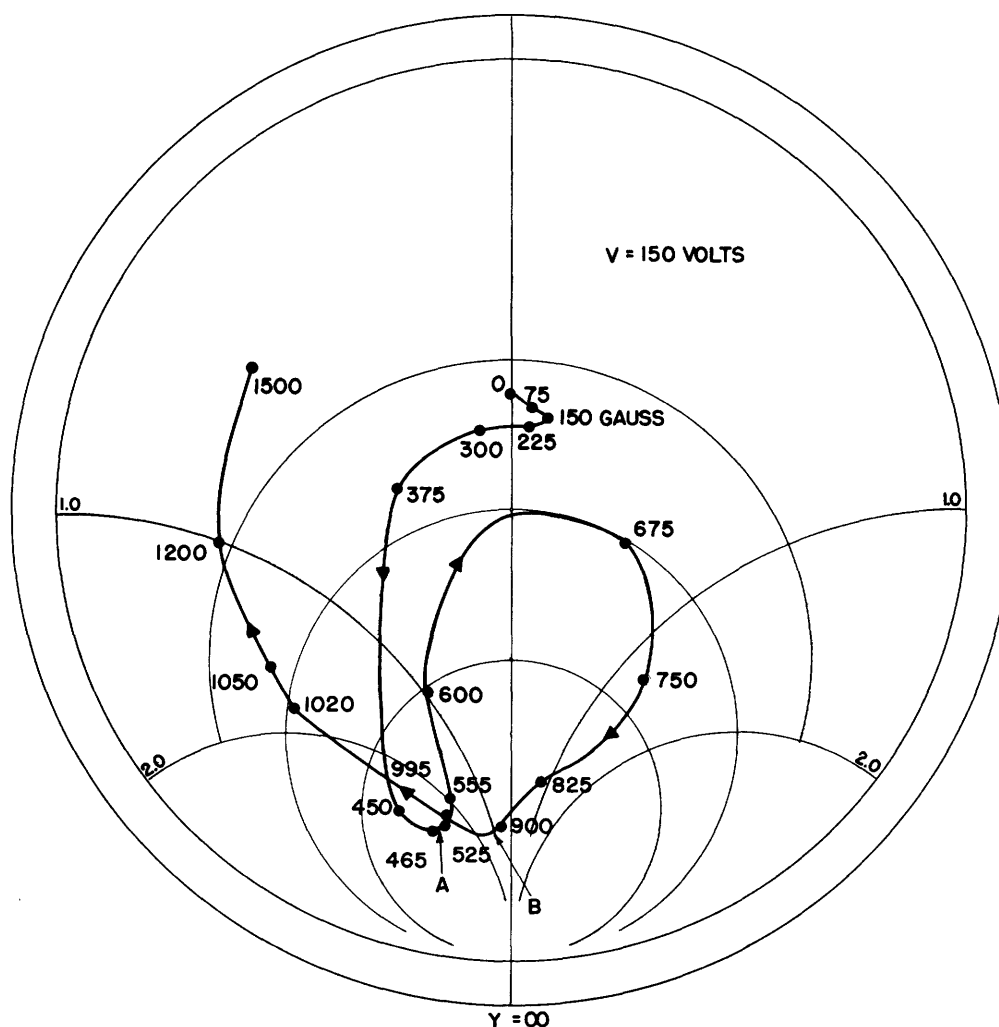


Fig.9 QK-61: input admittance as a function of magnetic field; anode voltage = 150 volts; incident r-f power = 14 mw (plotted from Fig.2).

Conclusions

The measurements described here allow us to draw a number of conclusions regarding the operation of the cutoff magnetron and its possible use as a circuit element.

1. In the particular tube tested, the maximum electronic tuning was about 1 per cent (~ 30 Mc/sec). By proper design of the resonator circuit, it should be possible to get much larger electronic interaction, and thus larger tuning ranges. Use of a smaller number of resonators would result in the r-f field penetrating closer to the cathode and thus producing stronger interaction. Similarly, the ratio of cathode to anode diameter might be varied. (It seems unlikely that the optimum value of this ratio would be the same for an oscillator as for a reactance tube.)

Electronic tuning can be controlled by either the magnetic field or the anode voltage. Voltage control seems to be the more practical of the two because of frequency response and power requirements.

2. The electronic loading is largest, and changes most rapidly, in the region of greatest electronic tuning. There seems to be no way of controlling this loss. This is in sharp contrast with beam tuning of magnetrons(9) where the loading can be reduced to zero by adjusting the transit time of the electrons through the r-f field.

3. Both tuning and loading are strongly dependent upon cathode emission. This indicates that even if the admittance characteristics of a cutoff magnetron were suitable for modulation purposes, the operation might be unstable if the cathode were temperature-limited. In these tests, the normal operating temperature of an oscillating magnetron appeared to be too low for use as a reactance tube.

4. Tuning and loading are functions of incident power level. Both of these decrease with increasing power.

5. This particular magnetron type (QK-61) seems to be quite unsuited for use as a reactance tube for modulating a self-excited oscillator, because of the large electronic loading. It might be used as an absorption modulator, as described by Gutton and Ortusi(5)(6). Without greater knowledge of the effect of anode-cathode diameter ratio and of resonator design, it is impossible to make any further general statements about the possible usefulness of such tubes.

6. No measurements of noise were made in the work reported here. Observations by other workers indicate that the cutoff magnetron is extremely noisy. Consequently, even though a structure could be devised which would provide a wide tuning range, its usefulness might be limited by the extra noise it introduced in the system.

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